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AN INDEPENDENT EVALUATION OF THE CH-46
SAFETY RELIABILITY AND MAINTAINABILITY
PROGRAM (SR&M)

by

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Thesis Advisor: W.M. Woods

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An Independent Evaluation of the CH-46 Safety Reliability and Maintainability Program (SR&M)

by

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ABSTRACT

This thesis is an independent partial evaluation of the Safety Reliability and Maintainability Program (SR&M). The two Measures of effectiveness which were used to see if the goals of this program were realized in the areas of maintainability and reliability are the Maintenance Manhours per Flight Hour and the Mean Flight Hours Between failures. Standard statistical analysis was performed utilizing the software packages GRAFSTAT and MINITAB.

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I. INTRODUCTION

The purpose of this thesis is to conduct an evaluation of the C-46 SR&M (Safety Reliability and Maintainability Program).

In December 1980, Boeing-Vertol was awarded the initial contract for the helicopter improvement program known as SR&M. This program is intended to extend the effective service life of the HH-46, CH-46D and CH-46E helicopters until the end of this century at a significantly reduced operating cost.

There are three major goals for the SR&M program:

- IMPROVED SATETY - reduce the number of personnel injuries and deaths that result from the malfunction of aircraft systems and its components.
- IMPROVED RELIABILITY - increase the mean flight hours between failures of aircraft components.
- IMPROVED MAINTAINABILITY - reduce the maintenance man hours per flight hour.

The first prototype SR&M modified CH-46E was flown in November, 1983. The first delivery to the Fleet Marine Force occurred in December, 1985. Marine Helicopter Training Squadron 204 (HMT-204) was the first Fleet Marine Force squadron to receive the modified aircraft.

Today there are over fifty modified aricraft in service. Data on number of failures, flight hours and maintenance of

these aircraft has been accumulated in the Navy's Maintenance Material Management System (3M). This data was used to conduct an evaluation of the SR&M program. The hoped for improvements in maintainability and reliability will be evaluated using the data accumulated on HMT-204's maintenance department.

This squadron was selected because it has been operating this aircraft the longest. It also appears to be a good candidate since it has consistent and regular flight hour requirements each month. Unlike deploying fleet squadrons that gear-up for major operation and experience changing environments; operating from Navy ships which results in a higher supply priority code, HMT-204 does not deploy.

A brief history of the CH-46 aircraft follows to emphasize how past modifications were made to improve or enhance the operational characteristics of the aircraft (i.e., airspeed, payload, range and all weather capabilities, etc.). The stated purpose of the SR&M modification is to improve the overall safety and reliability of the aircraft and its components. This should result in reduction of the maintenance cost associated with operating the CH-46E in the Fleet Marine Force.

The SR&M (Service Reliability and Maintainability Program) modified CH-46E Tandem-rotor helicoptor in use by the United States Marine Corps has come a long way in its 30 year history.

Boeing-Vertol began preliminary design and engineering of the helicopter in 1956. Construction of the first prototype began in May, 1957. The first flight of the aircraft took place on April 22, 1958. The United States Marine Corps first ordered the CH-46A in February of 1961. The CH-46A was powered by 2 General Electric T58-GE-8 1250 shp (shaft horse power) engines. This aircraft had a maximum take-off and landing weight of 21,400 pounds and could cover a 230 nautical mile range. This aircraft had little or no single engine capability. You could not maintain level flight with a single engine. The Marine Corps would eventually receive over 130 of this aircraft model.

All CH-46s delivered after July, 1966 are designated CH-46D. The CH-46D is essentially similar to the CH-46A except the aircraft was now powered by 2 General Electric T58-GE-10 1400 shp engines. This aircraft had a maximum take-off and landing weight of 23,000 pounds (1,600 pound increase) and could cover a 238 nautical mile range. This aircraft had a limited single engine capability. Aircraft could operate at a minimal rate of descent depending on aircraft load and outside ambient conditions, if one of the engines stopped operating. Another major change in the D model production was the addition of cambered rotor blades to improve the aerodynamic performance of the rotor system. By June, 1969 the Marine Corps had received its' 500th CH-46 aircraft.

All CH-46s delivered after July, 1968 are designated CH-46F. The same engines and rotor blades used in the D model were used during F model production. The addition of improved navigational and electronic equipment was the reason for model designator modification. The maximum take-off weight did not change. With the addition of 275 pounds of electrical equipment, the available payload was decreased accordingly. All D model CH-46s in the inventory also received the new equipment. This resulted in major differences in the electrical schematics and different operating procedures for each model in the event of certain electrical malfunctions. The production of CH-46Fs continued until 1971 when the last new CH-46 rolled off the assembly line. All future improvements and modifications would be made at the Naval Air Rework Facility (NARF) Cherry Point, North Carolina.

Boeing-Vertol modified 2 CH-46s in 1975 with 2 General Electric T58-GE-16 1870 shp engines. This model also included; crash attenuating seats for the pilots, a new crash and combat resistant fuel system, an improved rescue system and an updated navigational system. The Marine Corps accepted this program and agreed to modify 276 CH-46D/F to CH-46E configured aircraft. During August, 1977 the first CH-46E for the Fleet Marnie Force rolled out of the Naval Air Rework Facility (NARF) Cherry Point, North Carolina. The aircraft now had a maximum take-off and landing weight of

23,300 for internal cargo and could operate at a weight of 24,300 with an external load. Internal loads are limited to 23,300 pounds due to the load bearing limits of the main landing gear. The maximum range remained at 238 nautical miles. This aircraft has outstanding single engine characteristics; i.e., It can hover in ground effect at its maximum take-off weight under all but extreme ambient conditions. During this conversion the Navy and Marine Corps sponsored substantial testing that resulted in the acquisition and use of Fiberglass rotor blades. By 1980 there were 70 CH-46E configured with Fiberglass rotor blades. As a point of interest, with the significant reduction in maintenance required due to the Fiberglass rotor blades, the Second Marine Aircraft Wing (2nd MAW) played musical chairs with the Fiberglass rotor systems, ensuring that all squadrons deploying out of th continental United States left with the new rotor system installed on their helicopters. It took unitl 1984 to equip all the CH-46s in the Marine Corps inventory with the new and improved Fiberglass rotor system.

In December, 1980 Boeing-Vertol was awarded the initial contract for the helicopter improvement program known as Service Reliability and Maintainability (SR&M).

II. DATA

A. DATA COLLECTION

Discussions were held with personnel at the Navy Sea Logistic Center Navy Maintenance Support Office, Mechanicsburg, Pennsylvania to determine the availability of data needed to perform the evaluation analysis. It was decided that the Navy's Aviation Maintenance Material Management System (3M) had the best data available. The Navy's 3M data has wide and varied purposes.

- DOCUMENTATION - The 3M program provides records which document that scheduled and unscheduled maintenance is performed in accordance with set and established procedures.

- MANPOWER ALLOCATION - Squadron manning levels are determined by the number of aircraft and mission requirements. The squadron must document that they are working technicians the prescribed hours per day.

- SAFETY - All Collateral Duty and Quality Assurance Inspectors signatures appear on the VIDS/MAF (Visual Information Display System/Maintenance Action Form) to attest to the fact they have inspected the work and witnessed the required procedures called for in the Maintenance Manuals.

- INFORMATION - Copies of all VIDS/MAFs generated during the last ten flights and all "up" gripes are maintained in the Aircraft Discrepancy Book (ADB) for the crew to review before accepting the aircraft for flight operations.

- SPECIAL REPORTS - NAMSO 4790.A7298-01 is one type of special report available from the 3M system. Table I shows a typical selection of the data used.

TABLE I
SAMPLE FROM NAMSO 4790.A7298

PERIOD - MAY 86 THROUGH MAR 87
DATE - 15 JUL 87

RELIABILITY AND MAINTAINABILITY SUMMARY
FOR SELECTED EQUIPMENTS

NAMSO 4790 A7298-01
PAGE 53
ACFT - CH-46E

AIRCRAFT - CH-46E

WUC	NOMENCLATURE		TOTAL FLIGHT HOURS	TOTAL MAINT ACTIONS	MFHBMA	M-1 REPAIR FAILURE	TOTAL FAILURE	MFHBF	UNSCH MAINT MAN HOURS	MAINT M/H PER F/H	M/H PER MAINT ACT	EM7 PER MAINT ACT
24A16	HYDRAULIC PUMP/MOTOR	152579	150	1	150.0	0	0	-.-	4	.027	4.0	2.0
		154020	236	1	236.0	0	0	-.-	1	.004	1.0	1.0
		155308	204	1	204.0	0	0	-.-	1	.005	1.0	.5
		156453	311	1	311.0	1	1	311.0	3	.011	3.4	2.7
		156464	275	1	275.0	0	0	-.-	9	.031	8.5	4.0
		156472	233	1	233.0	1	1	233.0	2	.009	2.0	1.0
		157687	199	1	199.0	0	0	-.-	3	.015	3.0	1.5
		TOTAL	2,322	7	331.7	2	2	1,161.0	23	.010	3.3	1.8
24A17	APP FUEL SYSTEM INSTALLATION	155308	204	1	204.0	1	1	204.0	1	.005	1.0	1.0
		156453	311	1	311.0	0	0	-.-	5	.016	5.0	2.5
		TOTAL	2,322	2	1,161.0	1	1	2,322.0	6	.003	3.0	1.8
24A18	APP START HYDR SYSTEM EQPT INS	156453	311	1	311.0	0	0	-.-	1	.003	1.0	1.0
		156472	233	1	233.0	0	0	-.-	1	.002	.5	.5
		157687	199	1	199.0	0	0	-.-	1	.004	.8	.4
		TOTAL	2,322	3	774.0	0	0	-.-	2	.001	.8	.6
24A1B	APP ENGINE MOUNT INSTALLATION	155308	204	1	204.0	0	0	-.-	2	.011	2.3	2.3
		TOTAL	2,322	1	2,322.0	0	0	-.-	2	.001	2.3	2.3
24A1C	APP AIRFRAME MOUNT INSTALLATIO	154020	236	1	236.0	1	1	236.0	36	.153	36.0	18.0
		155308	204	1	204.0	0	0	-.-	1	.005	1.0	1.0
		156464	275	1	275.0	0	0	-.-	10	.035	9.7	4.8
		TOTAL	2,322	3	774.0	1	1	2,322.0	47	.020	15.6	7.8
24A1D	APP DRAIN TUBING INSTALLATION	154005	179	1	179.0	0	0	-.-	1	.003	.5	.5
		156453	311	1	311.0	0	0	-.-	3	.010	3.0	2.0
		TOTAL	2,322	2	1,161.0	0	0	-.-	4	.002	1.8	1.3
24A1F	APP GENERATOR CONTROL UNITS IN	152579	150	1	150.0	0	0	-.-	2	.016	2.4	1.1
		154005	179	1	179.0	0	0	-.-	3	.017	3.0	2.5
		154020	236	1	236.0	1	1	236.0	1	.004	1.0	1.0
		155308	204	4	51.0	0	0	-.-	16	.079	4.0	1.7
		156453	311	4	77.8	0	0	-.-	15	.047	3.7	2.3
		157688	249	2	124.5	1	1	249.0	2	.010	1.2	.8
		TOTAL	2,322	13	178.6	2	2	1,161.0	40	.017	3.0	1.7
24A19	NOC	156453	311	1	311.0	1	1	311.0	2	.006	2.0	1.0
		157688	249	1	249.0	0	0	-.-	4	.016	4.0	4.0
		TOTAL	2,322	2	1,161.0	1	1	2,322.0	6	.003	3.0	2.5
	TOT 24A10 AUXILIARY POWER PLAN	152579	150	7	21.4	1	1	150.0	81	.542	11.6	6.2
		153347	239	6	39.8	3	3	79.7	14	.059	2.4	1.6
		154005	179	3	59.7	1	1	179.0	7	.036	2.2	1.5
		154020	236	11	21.5	8	8	29.5	73	.310	6.6	3.5
		155304	47	1	47.0	0	0	-.-	8	.170	8.0	4.8
		155308	204	14	14.6	4	4	51.0	46	.227	3.3	1.8
		156453	311	13	23.9	4	4	77.8	65	.209	5.0	2.7
		156464	275	4	68.8	1	1	275.0	54	.196	13.5	5.4

The 3M data is not collected to be used for strict statistical analysis. This data does not include the actual flight hours between failures. Consequently some analysis that could provide specific statistical inferences could not be made. However, some interesting comparative results were obtained using total flight hours, total failures and total maintenance man-hours, Mean Flight Hours Between Failures (MFHBF) and Maintenance Man-Hours per Flight Hour (MMH/FH).

Observations made about the data base:

- Although the data was not collected under experimental conditions and has some shortcomings, it appears from examination of the data that both data samples have the same inherent set of shortcomings relative to their impact on statistical analysis.

- A general comparative analysis can be made with good credibility that assesses whether or not a significant decrease in MMH/FH was achieved.

- Some inferences can be made on the failure rates of key components as a function of the number of repairs previously made on the component.

Every Maintenance Action Form (MAF) completed by HMT-204, to document maintenance performed by squadron personnel on aircraft, is forwarded to the Navy's 3M system. This data was then tabulated by aircraft bureau number (serial number) to include the total number of maintenance actions performed, actual system/component failure, flight hours per aircraft and hours of maintenance performed (Table I).

A VIDS/MAF is generated in three ways:

- MAINTENANCE CONTROL PERSONNEL will issue MAF's to document and ensure preventive maintenance is completed according to flight time and calendar requirements.

- CREW CHIEFS or PLANE CAPTAINS will document aircraft discrepancies discovered during pre-flight and post flight inspections.

- PILOTS and CO-PILOTS will document aircraft discrepancies discovered during pre-flight and post flight inspections. It is the pilot's responsibility to complete MAFs covering all malfunctioning aircraft systems and inform Maintenance Control of his feelings about the aircraft's operational status at the completion of all flights.

Modifications to aircraft under the SR&M program were incorporated during the aircraft's scheduled Special Depot Level Maintenance (SDLM) cycle. Aircraft at Marine Corps Air Station (Helicopter), New River, with SDLM dates in 1985 were transferred to HMT-204. This accounts for the fact that HMT-204 was assigned 19 different aircraft during the time pre-SR&M data was collected. The 11 in the post SR&M sample include 1 that was sent back to NARF Cherry Point requiring extensive repair. HMT-204 is usually allocated 10 CH-46 aircraft.

At the time the data was requested from Mechanicsburg, the last month entered in the Navy's Aviation 3M System was March 1987. HMT-204 received its last SR&M modified aircraft during April 1986. This means May 1986 was the first month the squadron's 3M data could be retrieved by Unit Identification Code (UIC). Consequently, 11 months was the longest period of time post SR&M data was available for an

operational fleet squadron. HMT-204 received its first SR&M modified aircraft during December 1985. In order to keep as much similarity as possible between the two data samples it was requested that the 11 months prior to first SR&M delivery be used for the pre-SR&M data base. The periods for the 2 data samples are as follows: January 1, 1985 - November 30, 1985 for pre-SR&M (non-modified) aircraft and May 1, 1986 - March 31, 1987 for post SR&M (modified) aircraft.

The pre-SR&M sample contains 19 aircraft logging 2688 flight hours. The post SR&M sample contains 11 aircraft logging 2322 flight hours during their respective periods.

B. DESCRIPTION OF DATA

Following is a description of th data (Table I) requested from the Navy's Maintenance Support Office in Mechanicsburg, Pennsylvania.

- TOTAL FLIGHT HOUR - Flight hours reported by aircraft bureau number for sample period.
- TOTAL MAINTENANCE ACTIONS - The number of unscheduled maintenance actions reported in VIDS/MAF records.
- MEAN FLIGHT HOURS BETWEEN MAINTENANCE ACTIONS - (MFHBMA) The total flight hours divided by the number of maintenance actions initiated.
- TOTAL FAILURES - The number of maintenance actions that were confirmed as failures.
- MEAN FLIGHT HOURS BETWEEN FAILURES - (MFHBF) The total flight hours divided by the total number of failures.

- UNSCHEDULED MAINTENANCE MAN-HOURS - (UMMH) The number of man-hours expended in the performance of unscheduled maintenance as reported in VIDS/MAF records.

- MAINTENANCE MAN-HOURS PER FLIGHT HOUR - (MMH/FH) The total unscheduled maintenance man-hours divided by the total flight hour.

- MAINTENANCE MAN-HOURS PER MAINTENANCE ACTION - (MMHMA) The total unscheduled maintenance man-hours divided by the number of maintenance actions initiated.

III. HYPOTHESIS TESTING

A. HYPOTHESIS DEVELOPMENT

In this section we perform one-sided statistical test of hypothesis about the difference in the means of the maintenance man-hours per flight hour (MMH/FH) for the two data samples, i.e. pre-SR&M and post SR&M components. One of the stated goals of the SR&M program will be met if the maintenance man-hours per flight hour (MMH/FH) is lower for the post SR&M aircraft than it is for the pre-SR&M aircraft.

Before proceeding to hypothesis testing it was necessary to establish as acceptable distribution for MMH/FH. This was accomplished using standard goodness of fit tests. After entering numerous samples from both data bases into the software package GRAFSTAT, it was determined that the MMH/FH data could be Normalized using the ln (natural logarithm, base e) transformation. Figure 3.1 (histogram plot) and Figure 3.2 (Quantile-Quantile Plot) from GRAFSTAT display the transformed data ln(Y) for different WUCs fitted to the Normal Distribution. One way to summarize a distribution is to partition the data into several intervals of equal length, count the number of points in each interval, and plot the points as bar lengths is a histogram. [Ref. 2] A perfect Normal distribution is superimposed on the histogram. Figure 3.1 shows the Normal distribution to provide a good fit to the

data. In a Quantile-Quantile plot a perfect Normal distribution would plot as a straight line. [Ref. 2] Again the Normal distribution is a good approximation for the distribution of the data.

The Kolmogorov-Smirnoff statistic provided by GRAFSTAT was 0.049973 with a significance level of 0.8647. The Chi-Square value was 2.1776 with 6 degrees of freedom at a significance level of 0.90267. These results support to our assumption that the ln(MMH/FH) has a normal probability distribution.

Once the data was transformed, standard hypothesis testing procedures (see Gibra) [Ref. 1] were used. The hypothesis was designed to look for a significant difference in mean MMH/FH between the modified and non-modified aircraft. Specifically a one sided test of hypothesis was selected to detect if the mean of the transformed data for modified aircraft is substantially smaller than the mean of the transformed data for non-modified aircraft.

There are two ways the typothesis can be set up:

1) construct 1 $H_o : \mu_x - \mu_y \geq 0$
$H_a : \mu_x - \mu_y < 0$

construct 2 $H_o : \mu_x - \mu_y \leq 0$
$H_a : \mu_x - \mu_y > 0$

where μ_x = mean of a natural logarithm of the maintenance man-hours per flight hour for modified aircraft (post SR&M)

2) μ_y = mean of the natural logarithm maintenance man-hours for non-modified aircraft (pre-SR&M)

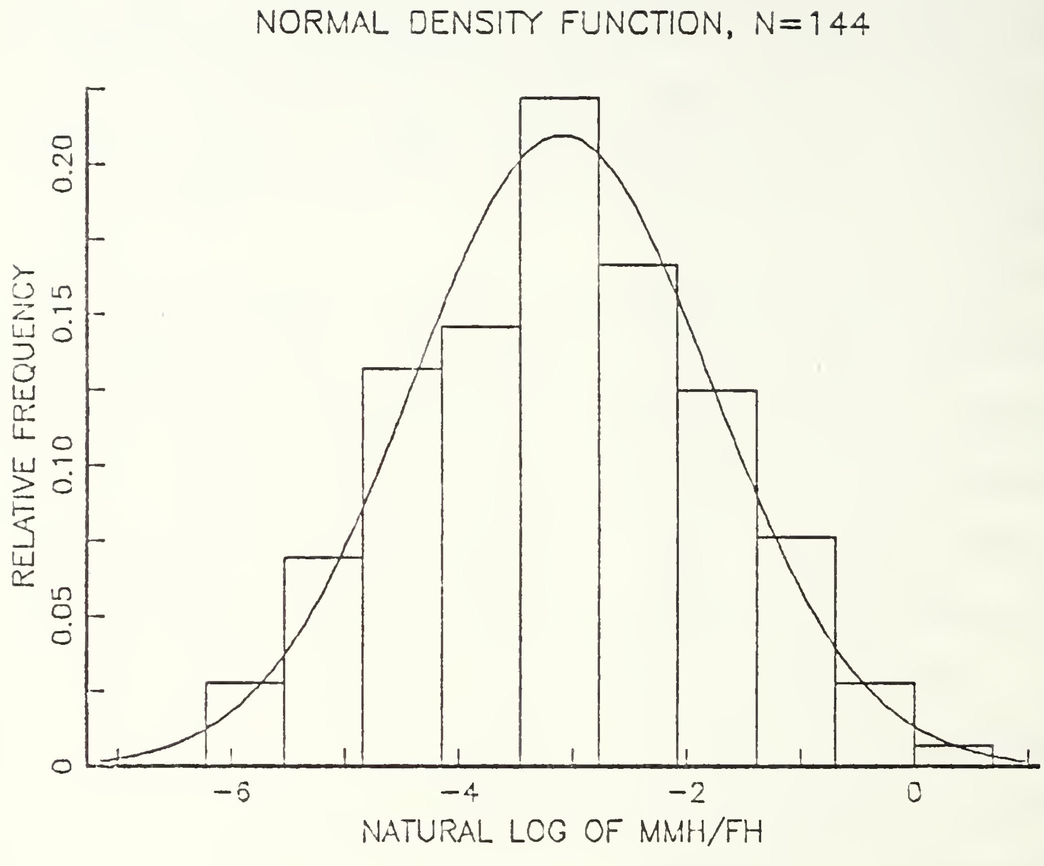

Figure 3.1 Histogram of Natural Log of MMHFH Fitted to Normal Dist

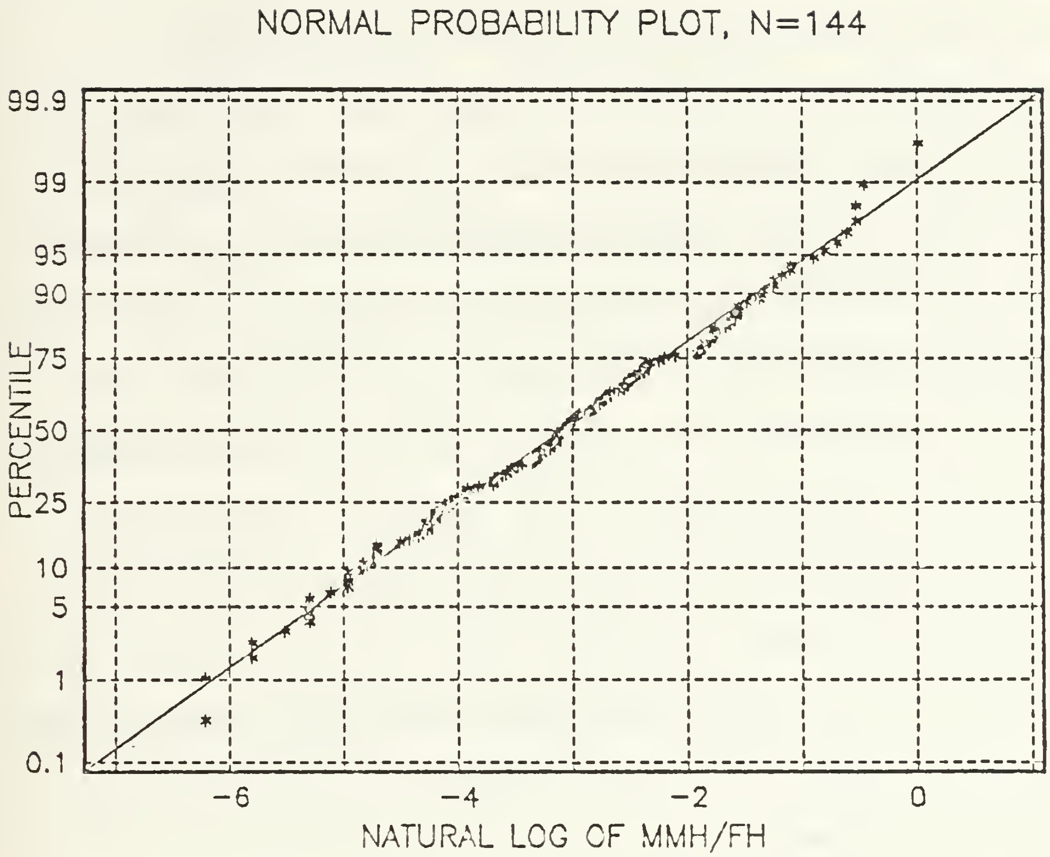

Figure 3.2 Quantile-Quantile Plot of MMHFH Fitted to Normal Dist

If the hypothesis is set up as described in construct 2 the null hypothesis ($H_o : \mu_x - \mu_y \leq 0$) would be accepted (and the claim of improvement "demonstrated") if:

$$\frac{\overline{X} - \overline{Y}}{s} < t_{\alpha\nu},$$

where s is the appropriate estimate of the standard deviation of $\overline{X} - \overline{Y}$, $t_{\alpha\nu,}$ is the upper $100(1 - \alpha)$ percentile point of a t-distribution with the appropriate degrees of freedom, ν, and X and Y are the sample means of the MMH/FH data for pre-SR&M and post SR&M respectively for the hardware unit under consideration. Note that $t_{\alpha\nu,}$ and s are both positive. Consequently we could accept the null Hypothesis that $\mu_x - \mu_y \leq 0$ even when $\overline{X} - \overline{Y}$ is positive but smaller than $s \cdot t_{\alpha}$. Consequently little or no actual reduction in MMH/FH would still make it likely that we would accept the null Hypothesis and the claim. This construct makes it easy to "demonstrate" an improvement without having effected a substantial improvement.

However, if we set up the Hypothesis as described in construct 1 with, the claim for improvement in the alternative Hypothesis ($H_a : \mu_x - \mu_y < 0$) it is much more difficult to show there has been an improvement. In this case we would reject H_o (and accept the claim for improvement) if:

$$\frac{X - Y}{s} < -t_{\alpha\nu},$$

This means not only must $(\overline{X} - \overline{Y})$ be negative it must be smaller than the negative number $s\ t_{\alpha,\upsilon}$. If we can say there is an improvement with the Hypothesis set up this way, there is a greater chance of there actually being an improvement in the maintainability Measure of Effectiveness (MOE) for a SR&M modified CH-46.

The raw data was converted into CMS (Conversational Monitor System in use at W. R. Church Computer Center) files utilizing the software package GRAFSTAT. Once a CMS file with the data was created the data could be moved into the software package MINITAB, and the Hypothesis testing portion of the data analysis was performed. The Hypothesis used was:

$$\text{construct 1} \quad H_o : \mu_x - \mu_y \geq 0$$
$$H_a : \mu_x - \mu_y < 0$$

The rejection rule used by MINITAB was:

$$\overline{X} - \overline{Y} < -s\text{-}t_{\alpha,\upsilon} \tag{3.1}$$

$$\upsilon = \frac{((S_x^2/n+S_y^2/m))^2}{[(S_x^2/n)^2/(n-1)] + [(S_y^2/m)^2/(m-1)]} \tag{3.2}$$

$$S^2 = \frac{(S_x{}^2)}{n} + \frac{(S_y^2)}{m} \quad . \tag{3.3}$$

where,

$\overline{X}$ = sample mean for post SR&M aircraft,

$\overline{Y}$ = sample mean for pre-SR&M aircraft,

n = number of aircraft is the post SR&M sample,

m = number of aircraft in the pre-SR&M sample,

α = level of significance,

υ = degrees of freedom (see equation 3.2),

S^2 = sample variance (see equation 3.3),

S_x^2 = sample variance for post SR&M aircraft,

S_y^2 = sample variance for pre-SR&M aircraft,

s = the square root of S^2

Recall that all of the above statistics are formed from the natural logarithm of the MMH/FH. The 100(1 - α)% upper confidence limit for $\mu_x - \mu_y$ is $\overline{X} - \overline{Y} + t_{\alpha,\upsilon}$.

The results from MINITAB Hypothesis testing are listed in Tables II and III. These tables list $\overline{X} - \overline{Y}$, upper 80% and 90% confidence limits and in the last column the largest confidence level γ for which the upper γ% confidence limit is zero. If the upper 100 (1 - α)% confidence limit is less than 0, the the Hypothesis $H_o : \mu_x - \mu_y \geq 0$ would be rejected in favor of $H_a : \mu_x - \mu_y < 0$ when testing the hypothesis at level α. It is usually more meaningful to the user to think of the γ values in the last column as the largest confidence he can have that $\mu_x - \mu_y < 0$. For example WUC 24A10 is the

auxiliary power plant. The data on this unit shows $\overline{X} - \overline{Y} = -0.349$. The upper 80% confidence limit for $\mu_x - \mu_y$ is -0.03. That is we are 80% confident that $\mu_x - \mu_y \leq -0.03$. Similarly we are 90% confident that $\mu_x - \mu_y < 0.14$. Also we are 82% confident that $\mu_x - \mu_y < 0$. It is interesting to note that there are 8 items of the 21 listed for which we are less than 50% confident that any improvement in mean maintenance manhours per flight huor (MMH/FH) has been reduced due to the SR&M program----using this data. The only difference between the two tables is Table II is by individual WUCand Table III is by major maintenance category.

TABLE II

RESULTS OF HYPOTHESIS TESTING BY WUC

WUC	$\overline{X} - \overline{Y}$	UPPER CONF LIMIT ON $\mu_x - \mu_y$ 80 %	90 %	LARGEST CONF LEVEL % $\mu_x - \mu_y < 0$ γ
11310	0.37	0.81	1.05	0.24
11560	-1.38	-1.00	-0.795	1.0
11610	-0.54	-0.12	0.10	0.86
11620	-1.31	-0.92	-0.695	0.99
13110	-0.09	0.32	0.50	0.52
13210	0.00	0.36	0.56	0.51
14130	-1.28	-0.84	-0.68	1.0
14170	0.24	0.74	1.02	0.35
142A0	-0.45	-0.01	0.24	0.80
14210	-0.01	0.44	0.68	0.50
14230	-0.04	1.39	3.16	0.51
14270	0.31	1.06	1.53	0.36
14280	0.62	1.10	1.30	0.063
15A10	-0.48	-0.26	-0.15	0.97
24A10	-0.34	-0.03	0.14	0.82
26110	0.17	0.74	1.06	0.40
26240	0.41	0.09	0.36	0.76
26610	-0.55	0.98	1.21	0.025
26810	1.31	2.35	3.00	0.15
29D90	1.09	1.44	1.63	0.0067
44114	-1.13	-0.69	-0.43	0.97

TABLE III

RESULTS OF HYPOTHESIS TESTING BY MAJOR MAINTENANCE CATEGORIES

WUC	$\overline{X} - \overline{Y}$	UPPER CONF LIMIT ON $\mu_x - \mu_y$ 80 %	90 %	LARGEST CONF LEVEL % $\mu_x - \mu_y < 0$ γ
11000	.007	0.54	0.65	0.51
12000	0.25	0.45	0.55	0.14
13000	-0.41	-0.20	-0.09	0.84
14000	-0.32	-0.13	-0.03	0.92
15000	-0.51	-0.30	-0.18	0.97
26000	-0.02	0.44	0.69	0.03
42000	0.33	0.54	0.65	0.17

IV. REGRESSION ANALYSIS

A. PROCEDURES

A regression analysis was performed to determine if the MFHBF was decreasing as a function of the previous number of failures. The paired data MFHBF and number of failures was entered into an APL (a mathematical programming language) workspace by work unit code (WUC). An APL program was developed to compute the mean flight hours for all aircraft by the number of failures. The results were then brought into a workspace in the statistical package GRAFSTAT. The paired data was plotted with the mean flight hours between failures (MFHBF) on the y-axis and the number of failures on the x-axis. The data for WUC 24A10 the Auxiliary Power Plant (APP) will be used and displayed in Figure 4.1 (pre-SR&M) and Figure 4.2 (post SR&M). The data for Major Maintenance Category 13000 the Landing Gear will be used and displayed in Figure 4.3 (pre-SR&M) and Figure 4.4 (post SR&M).

The Least Squares Estimates of the slope (b) and the intercept (a) were then computed by GRAFSTAT.

The Sum of Squares $\sum_{i=1}^{k} d_i^2$ is defined as:

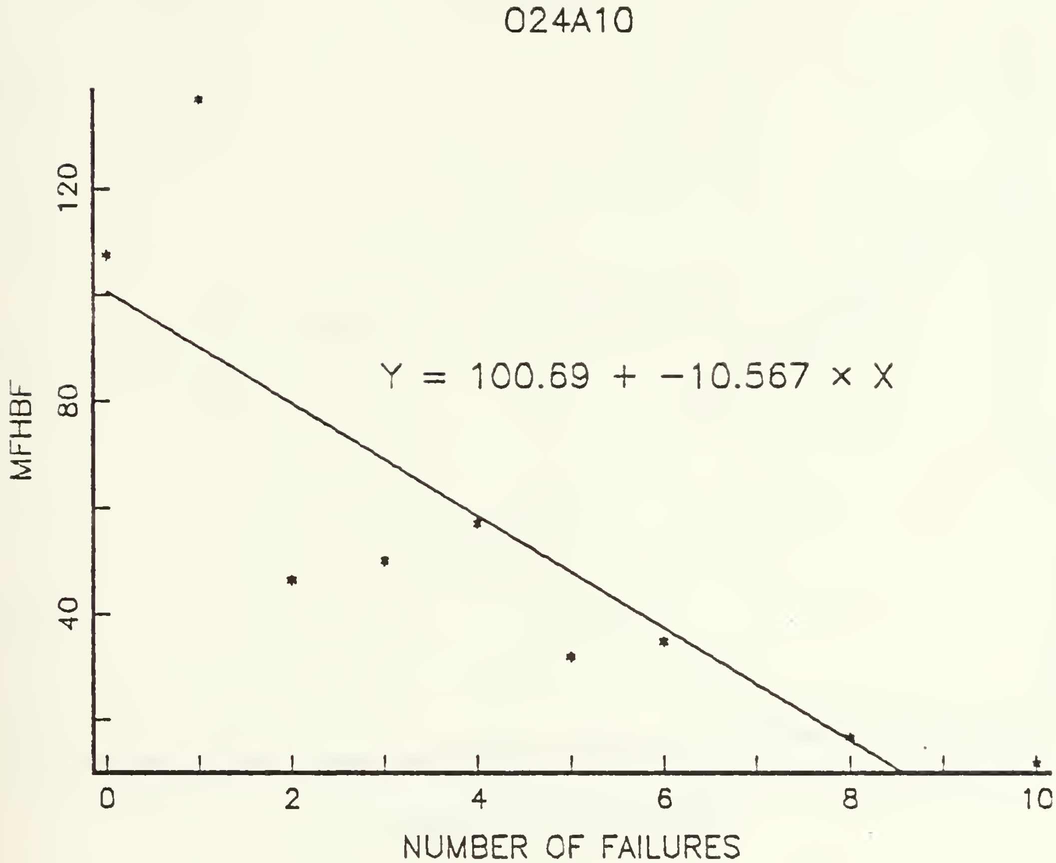

Figure 4.1 PRE-SR&M WUC 24A10

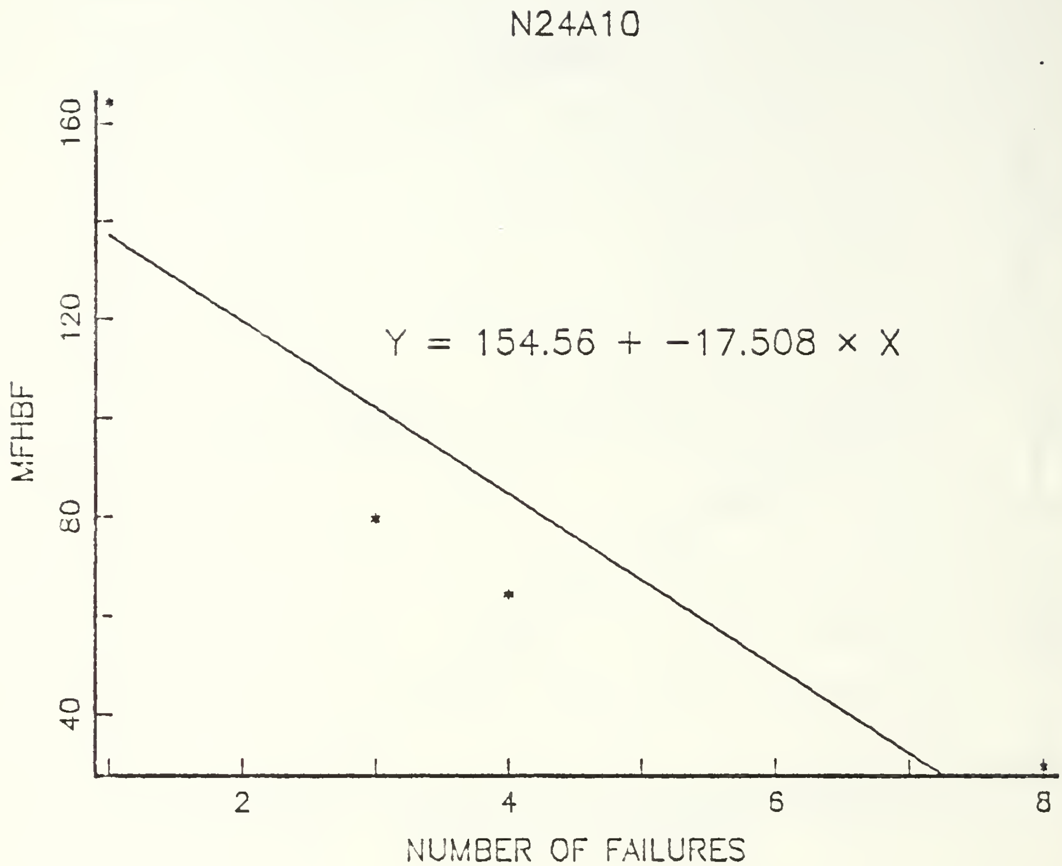

Figure 4.2 POST-SR&M WUC 24A10

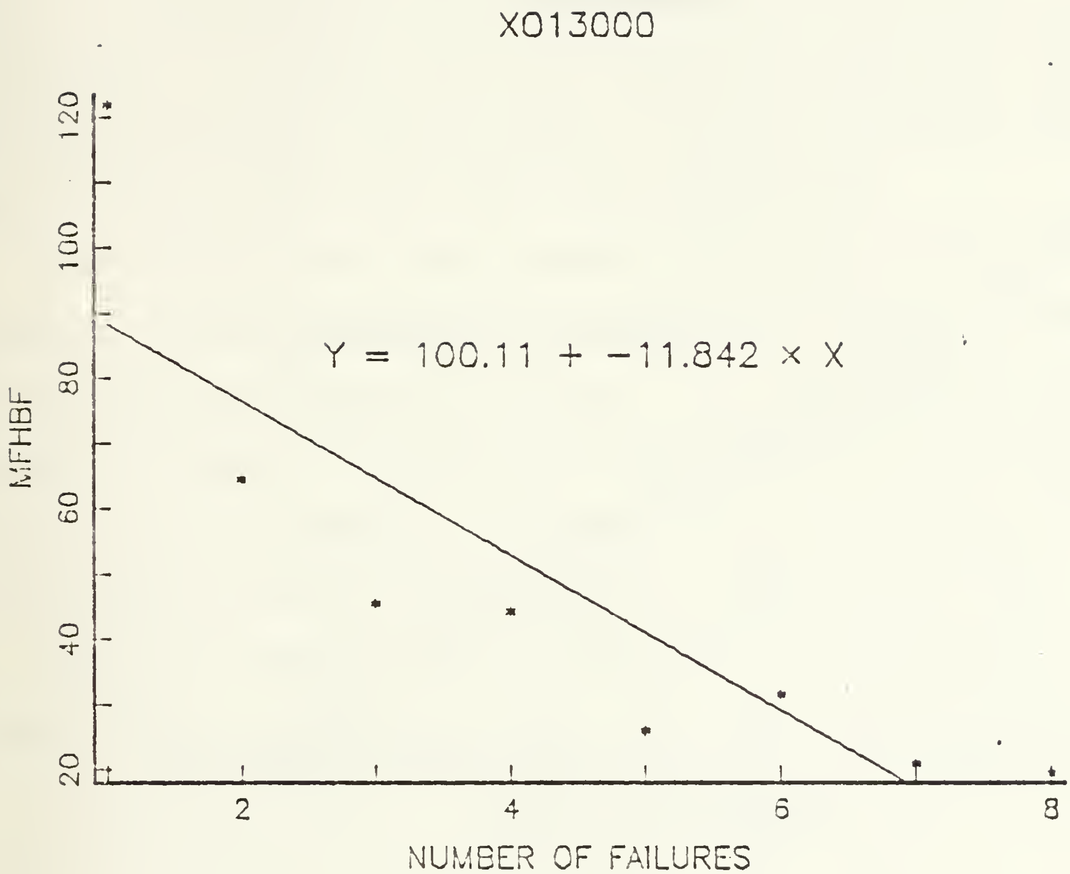

Figure 4.3 PRE-SR&M WUC 13000

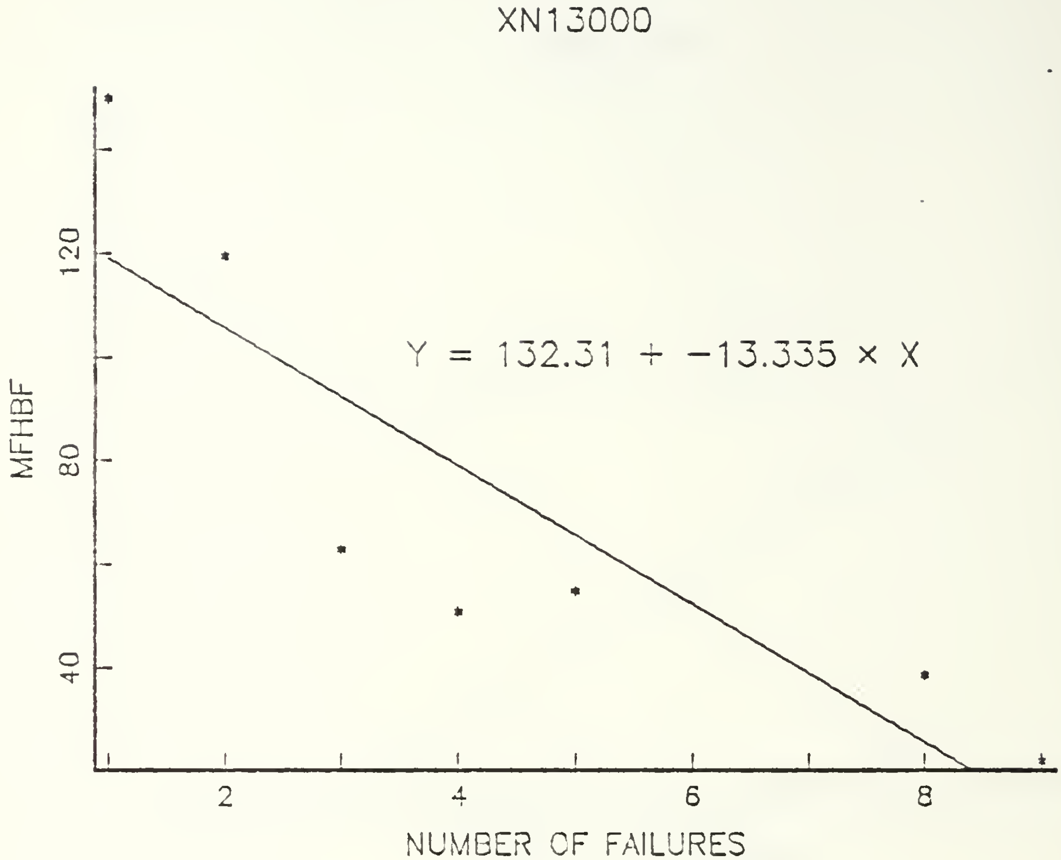

Figure 4.4 POST-SR&M WUC 13000

$$\sum_{i=1}^{k} d_i^2 = \sum_{i=1}^{k} [y_i - (a+bx_i)]^2. \tag{4.1}$$

When the left-hand side is minimized the values of a (intercept) and b (slope) describe the line y = ax + b that best fits the data using the method known as least squares regression. This was done to estimate the time until first failure (intercept) and the rate of decline in MFHBF (slope) per failure by work unit code for numerous WUC.

Table IV displays the computed values for the slope and intercept associated with the regression of MFHBF on number of failures for selected WUC units. They were computed by GRAFSTAT. Table V displays the same information for major maintenance categories. For example 13000 is the data for all WUC starting with the numbers 13---, the CH-46 airframe.

There are numbers in the table that are unrealistic, some WUC have increasing slopes, i.e., the part is less likely to require maintenance the more the aircraft is flown. These points are included to emphasize the problems with the data base, it is not perfect but the problems should be the same for both samples.

The data in Tables IV and V shows that the aircraft is likely to fly more hours before the new components experience their first failure. The numbers for WUC 24A10 non-modified aircraft are intercept 100.69 and slope -10.567, and intercept 154.56 and slope -17.508 for modified aircraft. The numbers

TABLE IV

LEAST SQUARES REGRESSION FIT BY WUC

	INTERCEPT			SLOPE	
WUC	OLD	NEW	%CHANGE	OLD	NEW
11220	169	251	148	-55.8	-50.2
11310	158	257	162	-34.4	-54.33
11550	102	124	180	-10.3	- 8.76
11560	123	222	180	-15.0	-36.5
11610	84	243	290	- 6.1	-34.2
11620	-	-	-	-	-
12510	-	-	-	-	-
13110	138	222	116	- 5.7	-61.2
13210	167	194	116	-40.5	54.8
14130	56	211	377	- 2.7	-35.9
142A0	166	178	107	-36.3	-14.3
14210	138	223	163	-27.0	26.8
14230	168	257	153	-49.8	-
14260	147	202	137	-19.1	-32.8
14270	154	296	192	63.8	-68
14280	167	204	122	-33.6	-35.9
24A10	101	154	151	-10.6	-17.5
26110	-	-	-	-	-
26120	178	241	136	-29.9	-60.2
26240	150	244	163	-17.5	-61.5
26460	142	246	174	-46.8	-13.0
26510	132	190	143	-17.8	-34.6
26610	133	168	127	-20.8	-21.8
44114	86	226	262	- 8.3	45.5

- not enough data for one of the samples to conduct LSR comparison.

for WUCs starting with 13---(Table V) non-modified aircraft are intercept 100.11 and slope -11.842, modified intercept 132.31 and slope -13.335. Hypothetically the modified aircraft can log approximately 54 more flight hours, on average before requiring maintenance on its APP. This is an improvement of 153% for the APP. In the case of WUC starting with 13---the improvement was 132%. This fact alone should reduce the cost of operating the aircraft in the Fleet Marine Force.

TABLE V

LEAST SQUARES REGRESSION FIT BY MAJOR MAINTENANCE CATEGORIES

	INTERCEPT			SLOPE	
WUC	OLD	NEW	%CHANGE	OLD	NEW
11000	11	20	182	-0.15	-0.36
12000	39	56	144	- 2.1	- 2.7
13000	100	132	132	-11.8	-13.3
14000	56	71	127	- 4.2	- 4.4
15000	11	22	200	- 0.2	- 0.4
26000	84	66	79	-6.4	-3.7
42000	40	22	55	- 1.9	- 0.5

The improvements in mean time until first failure range from a low of 107% to a high of 377%. It is interesting to point out in numerous cases the mean time until first failure was greatly improved while the slope was also a decreasing

negative number so after 4 or 5 failures the MFHBF was essentially equal for both modified and non-modified aircraft.

When the data was looked at grouped by major maintenance categories:

- 11000 Airframe
- 12000 Fuselage Compartment
- 13000 Landing Gear System
- 14000 Flight Controls
- 15000 Rotor System
- 26000 Drive system
- 42000 Electrical Power Supply

The improvements varied from a low of 55% to a high of 200%, in the mean time until first predicted failure.

The WUC analyzed were selected because they were directly impacted by one of the SR&M modifications. Mr. William Jennings, the Boeing-Vertol Technical Representative at Marine Corps Air Station (H) New River, North Carolina, was very helpful with this selection of WUC.

B. DECREASING TREND AND VARIANCE ANALYSIS

The data in Table IV and the regression charts, suggest that MFHBF is decreasing as the number of failures increases, i.e., items with 6 failures have lower flight hours between failures than aircraft with 1 or 2 failures? If this is actually the case it would be important to know the rate of decrease more accurately than can be determined from this

data base. It is necessary to have the actual flight times betweeen each failure in order to make this assessment. If MFHBF does decrease as number of failures accumulate, then the affect of the SR&M program washes out after some number of failures. It is also important to know this in order to more accurately estimate the reliability of each aircraft, i.e., the failure history of its components affect its reliability, Here it would be good to have the actual flight time between each failure. We have no information to confirm or deny that each failure was a separate and distinct problem.

It is also of interest to know if the variance of MFHBF changed as a function of the number of accumulated failures. That is, is s^2 for an item with 4 failures the same as for an item with 6 failures? To answer this question three items were examined.

In Table VI the number of failures is listed in the far left-hand column, the 3 selected WUC across the top and the associated variance for that number of failures is listed where appropriate. If there was no aircraft with the number of failures for that WUC the table was left blank. There is a wide range in the variance for all the components looked at. Just by looking at these three components we are confident is saying the variance is not equal among groups with different number of failures.

TABLE VI

VARIANCE OF FAILURE RATE

FAILURES	13110		24A10		44114	
	OLD	NEW	OLD	NEW	OLD	NEW
0	1292.7	2142.7	3894.3	0.0	0.0	1885.1
1	2908.9	0.0	722.0	4280.3	1022.7	3042.0
2	780.0	242.0	0.0	0.0		
3			125.0	89.8	214.2	
4			12.5	359.1	1.3	
5			0.0	0.0		
6			257.6	0.0		
7						
8			0.0	0.0	84.6	
9					0.0	

V. ADDITIONAL ANALYSIS

A. REGRESSION ANALYSIS OF MTBF (MEAN TIME BETWEEN FAILURES)

The analysis in Chapter IV indicated that mean flight hour per failure decreased as the number of failures (hence repairs) accrued against hardware. If this relationship is correct it has important implications for scheduling of maintenance--both in flight hours between repairs and in planning resource requirements. The 3M data used to make the analysis in Chapter IV does not provide sufficient detail to make an accurate analysis of the linear relationship between mean flight hour between failure and number of accured failures. The data needed to provide an accurate analysis is the actual flight hours between each failure for each type of component (by WUC or serial number) for which such analysis is desired. In particular if such an analysis is desired to be developed and maintained for the Auxiliary Power Plant (APP) units, then the actual flight hours between each failure of each APP unit must be kept by APP serial number.

This data would not only afford trend lines but would also permit the prediction of percentile points for the distribution of flight time to failure for APP units which have had previous failures (and repairs). That is, this type of data will allow us to make an estimate of number of flight hours, $t(\alpha, i)$, for which

$$P[T_i < t(\alpha_1 i)] = \alpha$$

where T_i denotes the flight hours to failure of an APP unit which has had i previous failures. For example, if $\alpha = 0.90$, APP units with 5 previous failures will fail again before $t(\alpha,i)$ with probability 0.90.

B. GENERAL ANALYSIS

The following analysis can be applied to any type of assembly i.e., APP, Flight Controls, etc. But the type of assembly is fixed in any specific application. The data always refers to flight hours to failure for the same type of assembly.

The model we use makes assumptions about the probabilty distribution. Specifically we assume the normal distribution. This assumption can be checked by appropriate analysis provided time between failure data is available, but whatever the appropriate probability distribution is determined to be, a similar analysis can be developed. Most of the analysis, i.e., the regression point estimates will still be valid regardless of the underlying distribution. The confidence bounds, however, would change. Also, if enough data is available so that five or more flight hour data points are available for each of the number of failure points (i.e., i = 0,1,2,...F) then the normality assumption might still be valid because we

will be using sample averages and the Central Limit Theorem will apply to yield and approximate Normal distribution.

Let t_{ij} denote the j^{th} flight time to failure for all components of the type under consideration which had i previous failures, $i = 0,1,2,...,F$, $j=1,2,...,n_i$

$$\text{Let } \bar{T}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} t_{ij}$$

$$\text{Let } \bar{\bar{T}} = \sum_{i=0}^{F} \sum_{j=1}^{n_i} T_{ij} / (\sum_{i=0}^{F} n_i)$$

$$\text{Let } f = (\sum_{i=0}^{F} i)/F.$$

We used the standard regression model, $T_{ij} = 1 + bi + e_{ij}$. Where e_{ij} is a random variable with mean 0 and variance σ^2 for all ij. Then

$$E(T_{ij}) = a + bi.$$

Then at each failure, $i = 0,1,2,...,F$ we have several observations as indicated in Figure 5.1.

We fit a regression line to this set of data using standard least squares methods. The least squares estimates a and b for a and b respectively are:

$$\hat{a} = \overline{T} - \hat{b}\overline{f}$$

$$b = (\Sigma(\overline{T}_i - \overline{T})i)/(\sum_{i=0}^{F} (i-\overline{f})^2)$$

Thus the data points $(T_{0,1},0)\ldots(T_{0,n},0)$, $(T_{1,1},1)\ldots$ $(T_{1,2},2)\ldots(T_{F,1},F)\ldots$(T&F,n.,F) yield the fitted line $T = a + bi$ in Figure 5.1.

To obtain the $t(\alpha,i)$ values we need the probability distribution for $\overline{T}_i$. We shall assume it is normal with mean $a + bi$ and variance σ^2. Then the α^{th} percentile point $t(\alpha,i)$ is $a + bi + \sigma Z_\alpha$ where Z_α is the α^{th} percentile point of the standardized normal distribution ($\mu = 0$, $\sigma^2 = 1$). The estimate of $t(\alpha_i)$ is

$$\hat{t}(\alpha,i) = \hat{a} + \hat{b}i + s(Z_\alpha)$$

where s^2 is the unbiased estimate of σ^2.

$$s^2 = \frac{\sum_{i=0}^{F} \sum_{j=1}^{ni} (t_{ij} - \overline{T}_i)^2}{\sum_{0}^{F} (n_i - 1)}$$

C. INFERENCES ON SYSTEM RELIABILITY

The appropriate equation for helicopter system reliability R_s is a function of the assembly reliabilities; i.e., $R_s = g(R_1,\ldots,R_k)$ where R_i = reliability of assembly i. In

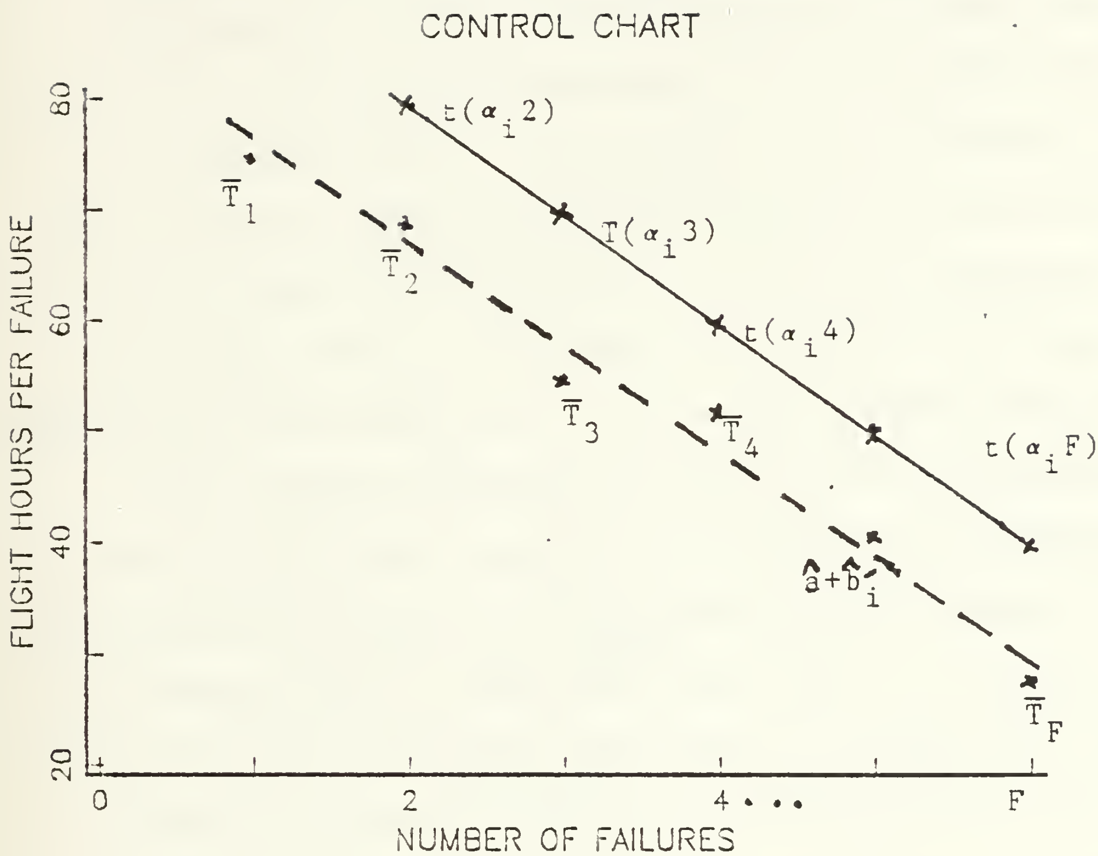

Figure 5.1 Control Chart

particular if the assemblies are chosen at high enough level and if failure times are statistically independent,

$$R_s = \prod_{i=1}^{K} R_i$$

The appropriate reliability block diagram will depend on the level of indenture of the assemblies. This in turn will determine the appropriate function $g(R_1, \ldots, R_k)$.

At a point in time any aircraft will be composed of assemblies with different failure and repair records. The point estimates of mission reliability of assembly k will be a function of $\hat{a}_k + \hat{b}_k i(k)$ where $i(k)$ is the number of previous failures on assembly k of that particular helicopter. The estimate s^2, for σ^2, and the assembly mission time t_k corresponding to system (helicopter) time t will yield a point estimate $\hat{R}_k(t_k)$ of $R_k(t_k)$ the mission reliability of the k component. These point estimates of the assembly mission reliability corresponding to system mission time t will give a point estimate of system reliability; namely,

$$R_s(t) = g(\hat{R}_1(t_1), \hat{R}_2(t_2), \ldots, \hat{R}_k(t_k)).$$

The preliminary analysis on Mean flight hours between failures provided in Chapter IV, indicate a strong decline as the number of failures increase. This will certainly have to level off at some point for the helicopter's lifetime even with repairs is certainly limited. These

preliminary results suggest that keeping the additional data needed to perform the analysis cited in this section could well be worth the effort.

VI. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The data in Table IV indicate the items for which we are confident that there is an improvement in the reliability of the C-46 SR&M modified aircraft. At present there is not enough operatonal data available to verify the extent of this improvement. Is the improvement due to operating with new components? Will the reduction in MFHBF for the modified aircraft result in more maintenance than presently indicated in the long run? These questions can only be answered with additional data analysis in the future when more complete data becomes available.

Of the Twenty-one WUCs considered, we can say nine of them showed a reduction in the MMH/FH. Five show an increase in the MMH/FH. The other seven show no significant change. This leads us to conclude the SR&M modified aircraft has some improved maintainability. We may also see greater improvements when mechanics become more familiar with the new systems/components.

B. RECOMMENDATIONS

Initiate a data collection program to collect flight hours between failure and flight hours between maintenance action peformed on each aircraft. Perform additional analysis

after the aircraft has been in the Fleet Marine Force and has accumulated more operational flight hours.

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2. Chambers, John M., and others, Graphical Method for Data Analysis, Durbin Press, 1983.

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